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Ion-Beam–Driven Resonant Ion-Cyclotron Instability*

H. W. Hendel,† M. Yamada, and S. W. Seiler
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540

and

H. Ikezi
Bell Laboratories, Murray Hill, New Jersey 07974

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The resonant ion-beam–driven electrostatic ion-cyclotron instability is identified. Measured dispersion relation and onset versus beam energy and density agree with numerical calculations based on a theory which includes beam-acoustic terms. After amplitude saturation, velocity-space diffusion of the beam ions is observed.

We report experimental results on a resonant, electrostatic ion-cyclotron instability destabilized by a low-energy ion beam injected parallel to the confining magnetic field into a target plasma. The interpretation is based on a theory which includes beam acoustic and target ion-cyclotron terms and on numerical calculations of the dispersion relation.

Instabilities driven by ion beams have recently attracted considerable interest in connection both with neutral-beam injection for fusion-plasma heating[1] and with space physics[2]: They may scatter particles and waves, effect energy transfer from beam to fusion plasma, and vary transport properties of beam and plasma. Ion injection, although differing from neutral injection in time evolution of ion-beam density and possibly beam-velocity distribution, is easier to set up and should also contribute to the understanding of neutral injection and of the relevant instabilities and their effects on the beam-plasma system. In isothermal ($T_e \simeq T_i$) fusion and Q-device plasmas, ion sound is strongly ion-Landau damped and not expected to play an important role.[3] However, ion-cyclotron waves can have a higher parallel phase velocity and may thus be destabilized more easily by an ion beam with $E_b > kT$.

The significant result of the present work is the detailed identification of the resonant ion-beam–driven electrostatic ion-cyclotron wave by measurements of ω and k and of threshold beam energy as function of relative beam density. The experiment is shown to be in agreement with numerical calculations extended from Perkins's theory of counterstreaming beams[4] to include a beam of variable density injected into a plasma at rest. After the wave amplitude saturates, the beam's parallel energy distribution was observed to flatten in the resonant particle region.

The theory considers a uniform, low-β, Maxwellian, target plasma in a constant uniform magnetic field B, with $T_e = T_{i\perp} = T_0$ and streaming velocity u_t, and an ion beam with streaming velocity u_b and velocity spread characterized by $v_{b\parallel} = (2T_{b\parallel}/M)^{1/2}$, $T_{b\perp} = T_0$. The ion beam is injected parallel to B in the z direction. All species are singly charged so that $n_e = n_{it} + n_{ib}$. The dispersion relation for electrostatic waves propagating almost perpendicularly to B ($k_\perp \gg k_z$), for $k_\perp \rho_e \ll 1 \lesssim k_\perp \rho_i$, is written

$$1+\frac{k_{De}^2}{k^2}+\frac{k_{Di}^2}{k^2}\left\{\sum_{n=-\infty}^{\infty} I_n(\lambda)e^{-\lambda}\left[1+\frac{\omega+k_z u_t}{k_z v_i} Z\left(\frac{\omega+k_z u_t+n\omega_{Ci}}{k_z v_i}\right)\right]\right\}$$
$$+\frac{k_{Di}^2}{k^2}\frac{n_{ib}}{n_{it}}\frac{T_i}{T_{b\parallel}}\left\{\sum_{n=-\infty}^{\infty} I_n(\lambda)e^{-\lambda}\left[1+\frac{\omega-k_z u_b+n\omega_{Ci}[1-(T_{b\parallel}/T_0)]}{k_z v_{b\parallel}} Z\left(\frac{\omega-k_z u_b+n\omega_{Ci}}{k_z v_{b\parallel}}\right)\right]\right\}=0, \tag{1}$$

where $k_{De(i)}^2 = 4\pi n_{e(it)} e^2/T_0$, $v_i = (2T_0/M)^{1/2}$, $v_{b\parallel} = (2T_{b\parallel}/M)^{1/2}$, and $\lambda = k_\perp^2 T_0/M\omega_{Ci}^2$. $Z(z)$ is the plasma dispersion function and $I_n(\lambda)$ is the modified Bessel function of nth order. We note that the parallel beam temperature decreases as $T_{b\parallel}/T_0 \simeq (v_i^2/2u_b^2)$ with increased ion-beam energy.[5]

This dispersion relation covers instabilities generated by both the kinetic and fluid interactions between the slow beam acoustic term and the ion-cyclotron mode of the target plasma.[4] Instability occurs when beam-ion inverse Landau damping overcomes target-ion cyclotron damping. Earlier theoretical work[6] used the approximation $|(\omega - k_z u_b)/(k_z v_{b\parallel})| > 3$ for the $n=0$ beam term, valid for the fluid regime but discarding instability based on the beam acoustic mode. Since the present experiment covers the regime $|(\omega - k_z u_b)/(k_z v_{b\parallel})| \simeq 1$, $|(\omega + k_z u_t - \omega_{Ci})/(k_z v_i)| \simeq 1$, we solved Eq. (1) by numerical computation. We note that because of the motion of the target plasma, the cyclotron frequency may be Doppler shifted ($\omega = \omega_{Ci}/2$ for $u_b = u_t$, in the lab frame), and in addition, cyclotron harmonics may be excited, so that $\omega = n\omega_{Ci}(1-\Delta)$. However, we expect lowest threshold for $\omega = \omega_{Ci}(1-\Delta)$, the wave due to coupling between the beam's slow-acoustic and the target plasma's fundamental ion-cyclotron modes.

The experiments were performed on the thermally ionized plasma of the Princeton University Q-1 device converted into a double-plasma machine[7,5]; see Fig. 1. A negatively biased mesh divides the plasma column into a 5-cm-long beam-extraction plasma and a 120-cm-long target plasma. The plasma diameter is 3.2 cm and the confining magnetic field 2–7 kG. When voltage is applied to the plasma column parallel to B through the ionizer (end) plates, the biased (-20 V) mesh (grid spacing $< \lambda_D$) prevents electron flow and the potential drop occurs in the sheath region of the mesh, thus generating an ion beam. Beam and target-plasma densities can be varied by regulating the neutral densities impinging on the ionizer plates. Beam-target ion collisions are negligible since $\lambda_{mfp} \simeq 10L$ for $E_b \simeq 2$ V and $\lambda_{mfp} \simeq 250L$ for 10 V (L is the machine length). The beam is generally injected on axis. For the target plasma, $n \simeq 10^9$ cm^{-3}, $T_i \simeq T_e = 0.3$ eV, the relative beam density is $n_b/n_t \simeq 0.1$–5, and $E_b/E_t = 0$–10^3. Probes are used to measure T_e, T_i, n_{it}, n_{ib} (determined with rotating, plane collectors), instability amplitudes and frequencies, and their radial profiles. An ion-energy analyzer (2 mm diam) with a 1-mm opening can be turned into beam, target, and perpendicular directions and moved radially. Wavelengths are obtained from the phase shift versus rotation of a double probe ($\lambda_\perp$) or versus distance to an axially or radially moving probe ($\lambda_\parallel$, $\lambda_\perp$).

Figure 2(a) shows measurements of the instability frequency versus B, for constant u_b, taken well above onset. The observed frequency is below the ion-cyclotron frequency, $\omega = \omega_{Ci}(1-\Delta)$, as expected from consideration of the target-plasma drift velocity, $(1-\Delta)/\Delta \simeq u_b/u_t$. Figure 2(b) displays instability frequency versus ion beam energy, for B = const. At onset, the frequency is about 35% below ω_{Ci}, and approach-

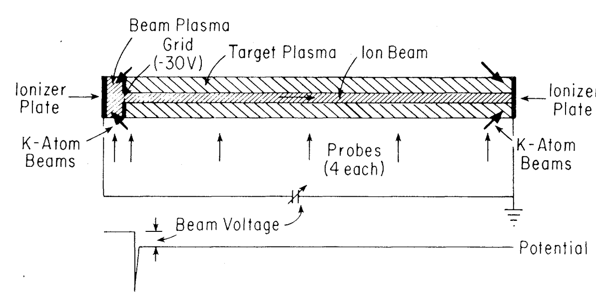

FIG. 1. Diagram of experimental setup.

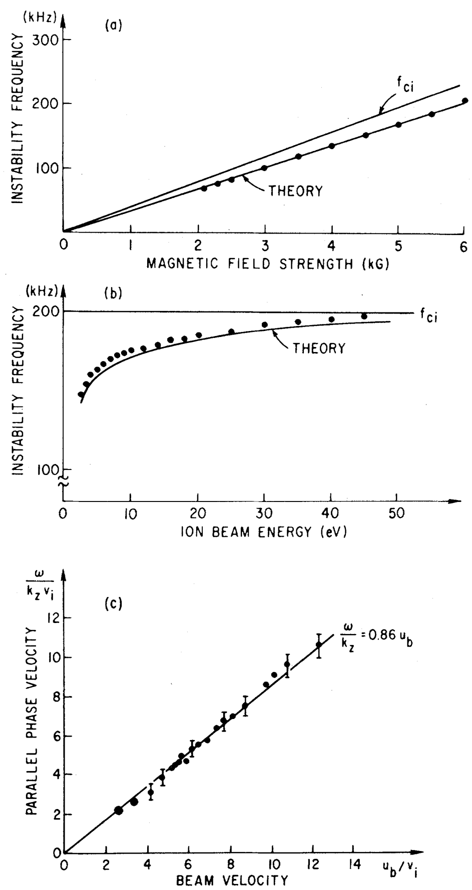

FIG. 2. Instability properties. (a) Frequency versus magnetic field strength. $u_b = 7\times10^5$ cm/sec. (b) Frequency versus ion-beam energy. $u_t = (4T_0/m)^{1/2}$, i.e., sound velocity. In the calculation, $k_\perp\rho_i = 0.7 = $ const; experimentally $k_\perp\rho_i$ is 1.7 at onset and 0.7 far beyond onset, with 30% error. (c) Parallel phase velocity versus beam velocity. Both axes normalized by $v_i = (2T_0/M)^{1/2}$.

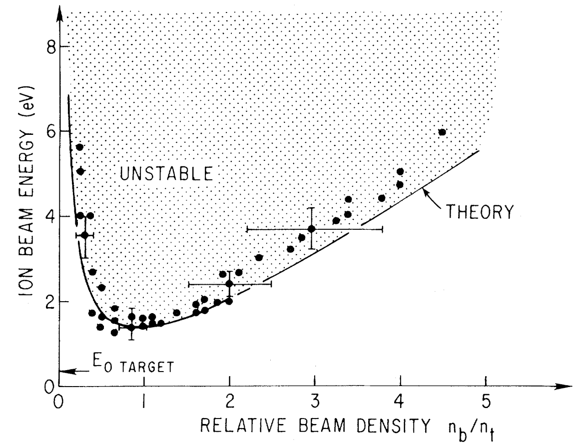

FIG. 3. Threshold beam energy versus relative beam density. The solid line was computed for the measured value of $k_\perp\rho_i = 1.7$, at onset. $|(\omega - k_z u_b)/k_z v_{b\parallel}| \simeq 0.5$–3.1.

es ω_{Ci} as the target-plasma drift velocity becomes negligible relative to the beam velocity, in agreement with the prediction. The resonance coupling between beam and phase velocities is demonstrated in Fig. 2(c), which indicates that the phase velocity is about 15% below the beam velocity, in agreement with the computer calculation. For Weibel's[6] purely growing mode, the beam velocity is $u_b = 2\omega/k_z$ when transformed to the experimental coordinates. We also measured $\lambda_\parallel$ versus B, for constant beam energy, and found the predicted behavior $\lambda_\parallel \propto 1/\omega_{Ci}$. Spatial growth of the wave was observed with the expected growth rate; converted to temporal growth rate, $\gamma/\omega_{Ci} \simeq 0.03$ at maximum. The wave is localized in the interior of the ion beam, with a maximum amplitude $\tilde{n}/n \simeq 15\%$. The radial wavelength was comparable to the beam diameter so that $k_\perp\rho_i \simeq 1$ as expected.

Figure 3 shows normalized threshold beam velocity as function of normalized beam density, for constant B. Onset occurs at lowest beam velocity for approximately equal densities of beam and target plasma. We note that two colliding, equal-temperature plasmas or beams would produce a symmetrical, parabolic u_b versus $\ln n_b/n_t$ plot. If, however, one of the plasmas (the beam) is reduced in (parallel) temperature (by acceleration), the increased inverse Landau damping leads to an asymmetric plot with lower onset values. Ion-beam–driven ion-cyclotron-wave results reported previously[8] were limited both experimentally by the setup and theoretically by the "cold-beam–cold-plasma" theory used or described different instabilities.[9] We also note that a mode at $\omega \simeq 0$ due to coupling of ion-acoustic–target and ion-cyclotron–beam terms at about zero frequency is suggested by Eq. (1). This mode could not be observed because of strong ion-Landau damping arising from $T_{it} \simeq T_e$.

Figure 4 shows the parallel energy spread (normalized by the initial value) of the ion beam as a function of beam energy. Since the instability is excited at the expense of parallel ion-beam energy by inverse ion-Landau damping, one expects deterioration of the beam energy at the fully developed stage of the instability. At this stage the instability satisfies the qualitative condition for the presence of nonlinear effects $[\omega_{\text{trap}} \simeq (2e\varphi/$

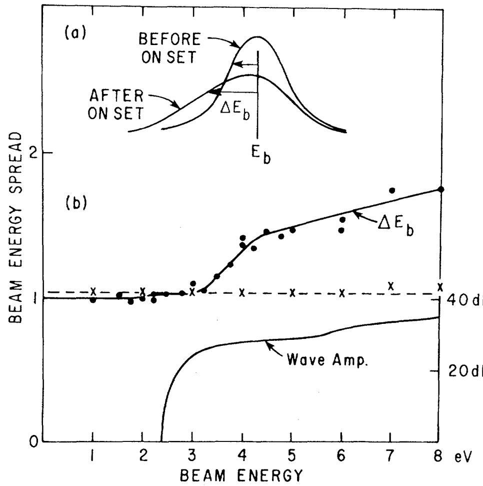

FIG. 4. Beam-energy spread with onset of instability. (a) Beam-energy distribution before onset and with saturated instability. (b) Beam-energy spread (normalized by the spread at $E_b = 1$ eV) and instability amplitude versus beam energy. Filled circles, $n_b/n_t \simeq 2$, instability present; crosses, $n_b/n_t \simeq 7$, instability absent.

$M)^{1/2}(2\pi/\lambda_{\parallel}) \simeq k_z v_i(\tilde{n}/n)^{1/2} \gg \gamma]$. The nonlinear wave-particle interactions were observed as flattening (velocity-space diffusion) of the beam distribution function on the low-energy side where the resonant particles exist, Fig. 4(a), which cannot be explained by a fluid theory.

Several important considerations arise from this work. The instability observed here may occur in neutral-injection fusion-plasma heating. The low threshold values of u_b/u_t measured are due to the reduction of beam parallel temperature with beam acceleration. As the beam density is increased to about 10% of the target-plasma density, the instability can be excited, depending on the shape of the distribution function, i.e., transient (narrow beam spread) or steady-state (wide-spread, small-slope) ion beam. Colliding-beam tokamaks[10] may be expected to be unstable during the transient switch-on phase (density ratio is 1 and beam spread narrow) but steady-state operation may lead to stable, wide, velocity distributions. In linear basic-research devices, effects on the target plasma due to beam injection cannot be detected easily, because of the insufficient confinement. However, increased energy transfer from the beam has been demonstrated in this work, which might affect better confined plasmas.

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†On leave from RCA Laboratories, Princeton, N. J. 08540.

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